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Headline Article
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Tungsten Isotopes, Formation of the Moon, and Lopsided Addition to Earth and Moon

--- A distinct difference in tungsten isotopic composition between the Moon and Earth is consistent with the Moon and Earth starting with the same isotopic composition, but then modified by late accretion of different amounts of chondritic asteroids.

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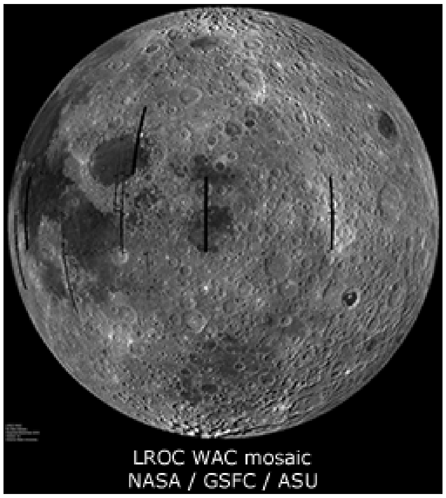

LROC WAC mosaic
NASA / GSFC / ASU

Two studies use vast improvements in measuring tungsten (W) isotopic composition to show that the Moon has a higher $^{182}W/^{184}W$ ratio than does the modern terrestrial mantle. The studies, done by Mathieu Touboul and colleagues at the University of Maryland, USA and Thomas Kruijer and colleagues at Westfälische Wilhelms University, Münster, Germany, required developing improved isotope separation and measurement techniques in order to make the measurements accurate and precise enough to see the small difference between lunar and terrestrial samples. The Moon has $^{182}W/^{184}W$ about 25 parts per million higher than the Earth. This is consistent with an interesting story told in both papers: the Moon and Earth both had the same W isotopic composition after the giant impact that formed the Moon, but the Earth acquired a disproportionate amount of chondritic material afterwards, which decreased the terrestrial $^{182}W/^{184}W$ value. The idea is consistent with current models of the numbers of projectiles that could have intersected the Earth-Moon system as planetary accretion was winding down. The implication is that immediately after the Moon formed it had the same tungsten isotopic composition as the Earth, an important fact that models for the giant impact origin of the Moon must explain.

References:

- Kruijer, T. S., Kleine, T., Fischer-Gödde, M., and Sprung, P. (2015) Lunar Tungsten Isotopic Evidence for the Late Veneer. *Nature,* v. 520, p. 534-537, doi:10.1038/nature14360. [**abstract**]
- Touboul, M., Puchtel, I. S., and Walker, R. J. (2015) Tungsten Isotopic Evidence for Disproportionate Accretion to the Earth and Moon. *Nature,* v. 520, p. 530-533, doi:10.1038/nature14355. [**abstract**]
- **PSRDpresents:** Tungsten Isotopes, Formation of the Moon, and Lopsided Addition to Earth and Moon--**Short Slide Summary** (with accompanying notes).

Isotopes and Moon Formation

The relative abundances of the **isotopes** of a given element provide clues to the chemical and physical processes involved in the origin of the raw ingredients (for example, the mix of **presolar** and **nebular** grains), primary **differentiation** (including formation of metallic cores), and subsequent chemical evolution of planetary bodies. Past results have indicated that the Moon and Earth have the same isotopic compositions of the highly **refractory elements** such as tungsten (W) and titanium (Ti); see **PSRD** article: **Titanium Isotopes Provide Clues to Lunar Origin**. More **volatile elements**, such as zinc, have distinctly different isotopic compositions in Earth and Moon. The Moon is enriched in the heavier ^{66}Zn isotope compared to ^{64}Zn, suggesting loss of some zinc during formation of the Moon; see **PSRD** article: **Zinc Isotopes Provide Clues to Volatile Loss During Moon Formation**. However, things are not so simple. The isotopes of W and Ti vary throughout the Solar System, so it is reasonable to expect that the giant impact event that formed the Moon would have involved two objects with different isotopic compositions of W and Ti, and in fact different isotopic compositions of other elements as well. (For a discussion of the big impact idea and some of the isotopic issues, see **PSRD** article: **Compositional Balancing Before Moon Formation**.) A final complication in determining whether the Moon and Earth differ in isotopic composition is that some of the ^{182}W is formed by the decay of radioactive ^{182}Hf (hafnium), which has a half-life of only 8.9 million years. Thus, it is in principle possible that the tungsten isotopic ratio was increased by ^{182}Hf decay. However, assorted chronological studies indicate formation of most lunar rocks at least 100 million years after formation of the Solar System, long enough for ^{182}Hf to have decayed to nothing, or close enough to nothing for all geochemical practical purposes.

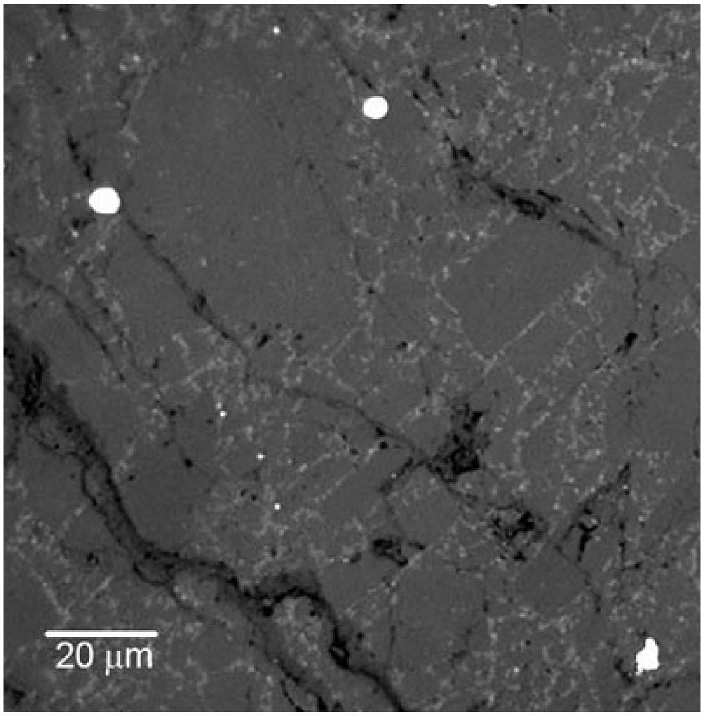
As analytical techniques improved, cosmochemists are able to discern small differences in isotopic compositions. In the case of tungsten, the difference between Earth and Moon is only about 25 parts per million. A tiny difference, but it needs explaining.

Tricky Measurements and Corrections

The first hints began to appear in 2007 in a paper by Mathieu Touboul and others (including Thorsten Kleine, second author on the paper led by Thomas Kruijer listed above). The problem was that the analytical uncertainties were too large to definitively show that the Moon had higher ^{182}W/^{184}W than the Earth. The nominal average value in four rocks was 9 parts per million, but that was plus or minus 10 parts per million. Cosmochemists are much too fussy to accept such large error bars. During the intervening years, the uncertainty has been driven down to acceptable levels.

Another interesting complication is that as lunar rocks are exposed to **cosmic rays** on or near (within a meter of) the surface, a fraction of the small amounts of tantalum-181 (^{181}Ta) in them is converted to ^{182}W. This secondary process messes up the primary lunar tungsten isotopic composition. To avoid this, Mathieu Touboul and colleagues physically separated metallic iron from lunar impact melt breccias. In contrast, Thomas Kruijer and his colleagues measured whole rock samples without separating the metallic particles, but used hafnium isotopes to monitor possible cosmic ray effects. Metallic iron contains virtually no tantalum, so the cosmic exposure problem is eliminated. To be sure of this, the analyzed samples have relatively short exposure times, between 2 and 24 million years. This does not seem short compared to a human lifetime, but many lunar rocks have cosmic ray exposure times of hundreds of millions of years. For rocks with long exposure to cosmic rays (hundreds of millions of years) the tungsten isotopic composition is altered somewhat, so Touboul and colleagues analyzed rocks with short exposure ages only. An important but reasonable assumption is that the metallic iron soaks up a lot of tungsten to make measurements feasible and that the tungsten isotopes equilibrated with those in the silicate at the time the rocks formed. Experiments and the measurements on samples indicate that these conditions are met.

Impact Melt from Lunar Breccia -- Apollo 67915

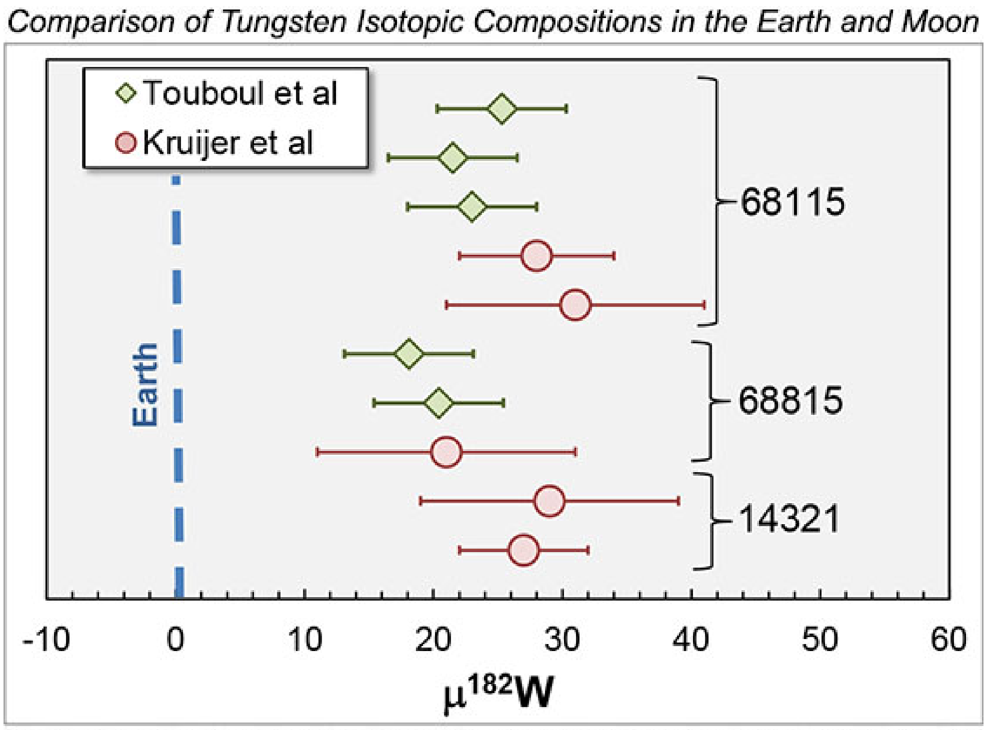


(Photo by Jeff Taylor, University of Hawaii.)

Microscopic image taken in reflected light of an impact melt from lunar breccia 67915 (not one of those measured by Touboul or Kruijer). The bright blobs are metallic iron; it is not abundant but is important as it equilibrates with the silicate (rocky) melt and scarfs up all the tungsten, but none of the tantalum. The gray and light gray areas are plagioclase and pyroxene, respectively.

Moon and Earth Have Different Tungsten Isotopic Compositions

The results from both research groups are shown in the diagram below. It plots the measurements as the ratio of $^{182}W/^{184}W$ in the Moon to $^{182}W/^{184}W$ in the Earth's mantle, in parts per million and expressed as $\mu^{182}W$. This procedure puts Earth at zero. There are differences between the two sets of measurements on the same lunar rocks, which reflect the details of analytical procedures and corrections for tungsten incorporated into the impact melts from the large impactors that made large lunar craters. But these do not matter in the grand scheme. It is blatantly clear that the Moon has higher $^{182}W/^{184}W$ than does the Earth, with a mean value of $\mu^{182}W$ of between 20 and 25 parts per million. This does not seem to be a particularly significant difference between Earth and Moon, but it leads to important conclusions about the addition of **siderophile** elements to the early Earth and Moon.



(Compiled from Kruijer *et al*., 2015, *Nature*, v. 520, p. 534-537 and Touboul *et al*, 2015, *Nature*, v. 520, p. 530-533.)

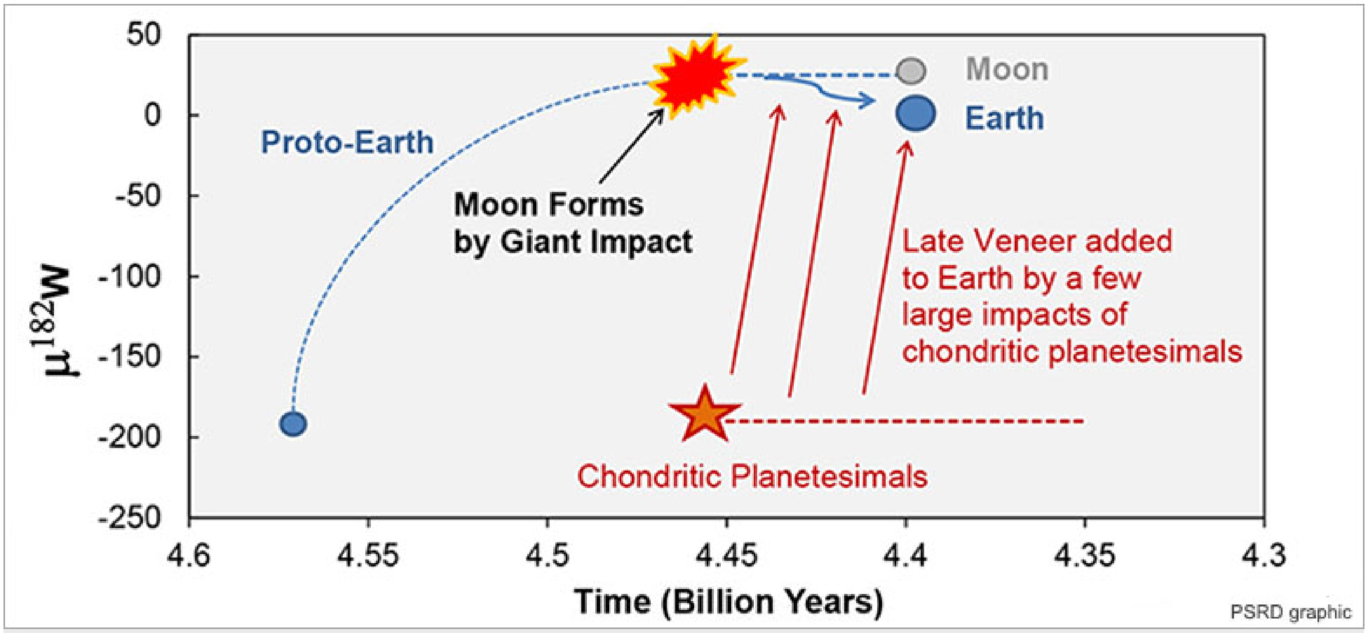
μ^{182}W values (diamonds and circles) from each paper plotted by lunar rock type. The rocks range in composition, but all fall clearly far to the right of the Earth value of zero. μ^{182}W is simply the ratio of ^{182}W/^{184}W in the Moon to ^{182}W/^{184}W in the Earth's mantle, expressed in parts per million (hence the μ symbol). Data take into account the effects of cosmic ray exposure. Numbers in the right column are lunar rock numbers; those beginning with 6 were collected by the Apollo 16 mission, whereas rock 14321 was collected by Apollo 14.

A Few Biased Impactors

A venerable but still debated idea in cosmochemistry is that the Earth received a late gift of siderophile elements to the mantle after the core had formed. When the metallic core dribbled to the center of the Earth, it gobbled up siderophile elements, removing them almost completely from the rocky mantle. However, the upper mantle of the Earth contains about 100 times the concentration expected if it equilibrated with vast amounts of metallic iron. This led to the idea that the elements were added to the Earth after the core formed. This extra addition of siderophile elements would have come from additional accretion of asteroids or comets. The idea is called the "late veneer." Using the concentrations of siderophile elements in chondritic meteorites as a guide, cosmochemists have calculated that Earth would have received between 0.3 and 0.8 wt% of additional material after core formation. Naturally, not everyone agrees with the late veneer hypothesis. For example, see the **PSRD** brief report: **Making an Argument Against the Late Veneer Hypothesis for Mars**, which applies to Earth, too.

Touboul and Kruijer and their colleagues test the idea that the difference between the ^{182}W/^{184}W ratio in the Earth and Moon is due to the late addition of only a few big planetesimals. Smaller ones undoubtedly peppered both bodies, but the largest ones account for most of the material added to the Earth and Moon. On the basis of the concentrations of siderophile elements in the terrestrial mantle and the Moon, both teams estimate that the Moon would have received less than 1% of the mass of material the Earth received. They calculate that if the late veneer was composed of chondritic rock, which has a μ^{182}W of about -200, it is likely that the Earth and Moon had the same μ^{182}W immediately following lunar formation by the giant impact.

Timing of Late Addition of Different Amounts of Chondritic Asteroids to the Moon and Earth



Cartoon illustrating the idea that the Moon and Earth began with the same tungsten isotopic composition (μ^{182}W), but end up different. [Do not be fooled by the quantitative look of the illustration, although the Moon-forming impact is plotted at about the right time and the μ^{182}W values for the Moon (grey), Earth (blue), and chondritic planetesimals (orange star) are also about right.] The idea is that the Earth forms with a μ^{182}W value (not really known so started at an arbitrary place in this illustration with μ^{182}W the same as chondritic meteorites) that gradually increases. The giant impact that forms the Moon leads to the Earth and Moon having the same tungsten isotopic composition. However, addition of a few chondritic impactors lowers the terrestrial value episodically until it reaches its current value of about 25 parts per million lower than the Moon.

Implications for Lunar Origin

If the interpretation by Touboul, Kruijer, and their coauthors that the Earth and Moon had the same tungsten isotopic composition after the giant impact is correct, this "constitutes a fundamental constraint on any successful model of lunar origin," as Kruijer and colleagues state at the end of their paper. Tungsten isotopic compositions range in planetary bodies throughout the Solar System, as shown by the large difference in μ^{182}W between chondrites and the Earth in the diagram above. If two random planetary bodies hit each other, they ought to vary in isotopic composition, implying that the Moon and Earth would have different isotopic compositions, unless processes in the complicated disk surrounding the Earth after the impact allowed the isotopes to equilibrate. This could happen for oxygen (see **PSRD** article: **Compositional Balancing Before Moon Formation**), but may not be efficient for refractory elements like tungsten.

The problem is not solved yet. We need to know more about core formation. Specifically, we need to know how efficiently the sinking metallic iron reacted with the mantle to deplete it in siderophile elements, the motivation for the need for the late veneer. The models proposed by Touboul, Kruijer, and their coworkers absolutely require siderophile element stripping from the mantle via metal from the giant impactor, otherwise the tungsten data would not be self consistent with the highly siderophile element data. An unknown is the extent to which the sinking metal exchanged tungsten with the surrounding mantle as it passed through on its way to the core. We also need to know the effects of pressure on partitioning of elements between silicates and metallic iron. And we need to figure out how much of the giant impactor's metallic core ended up in the disk from which the Moon formed and how much then went into the Moon.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Tungsten Isotopes, Formation of the Moon, and Lopsided Addition to Earth and Moon--**Short Slide Summary** (with accompanying notes).

- Kruijer, T. S., Kleine, T., Fischer-Gödde, M., and Sprung, P. (2015) Lunar Tungsten Isotopic Evidence for the Late Veneer. *Nature*, v. 520, p. 534-537, doi:10.1038/nature14360. [**abstract**]
- Martel, L. (May 2015) Making an Argument Against the Late Veneer Hypothesis for Mars, *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/CosmoSparks/May15/HSE-highPT.html**.
- Taylor, G. J. (Feb 2008) Compositional Balancing Before Moon Formation, *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Feb08/EarthMoonFormation.html**.
- Taylor, G. J. (May 2012) Titanium Isotopes Provide Clues to Lunar Origin, *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/May12/Ti-isotopes-EarthMoon.html**.
- Taylor, G. J. (Dec 2012) Zinc Isotopes Provide Clues to Volatile Loss During Moon Formation, *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Dec12/Zn-isotopes-EarthMoon.html**.
- Touboul, M., Kleine, T., Bourdon, B., Palme, H., and Wieler, R. (2007) Late Formation and Prolonged Differentiation of the Moon Inferred from W Isotopes in Lunar Metals, *Nature*, v. 450, p. 1206-1209, doi:10.1038/nature06428. [**abstract**]
- Touboul, M., Puchtel, I. S., and Walker, R. J. (2015) Tungsten Isotopic Evidence for Disproportionate Accretion to the Earth and Moon. *Nature*, v. 520, p. 530-533, doi:10.1038/nature14355. [**abstract**]

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